Quarterly Technical Report

Reactive Multiphase behavior of CO_2 in Saline Aquifers beneath the Colorado Plateau

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ABSTRACT

Gas reservoirs developed within the Colorado Plateau and Southern Rocky Mountains region are natural laboratories for studying the factors that promote long-term storage of CO_2. They also provide sites for storing additional CO_2 if it can be separated from the flue gases of coal-fired power plants in this part of the U.S.A. These natural reservoirs are developed primarily in sandstones and dolomites; shales, mudstones and anhydrite form seals. In many fields, stacked reservoirs are present, indicating that the gas has migrated up through the section. There are also geologically young travertine deposits at the surface, and CO_2-charged groundwater and springs in the vicinity of known CO_2 occurrences. These near-surface geological and hydrological features also provide examples of the environmental effects of leakage of CO_2 from reservoirs, and justify further study.

During reporting period covered here (the second quarter of Year 2 of the project, i.e. January 1 – March 31, 2002), the main achievements were:

- Field trips to the central Utah and eastern Arizona travertine areas to collect data and water samples to support study of surface CO_2-rich fluid leakage in these two areas.
- Partial completion of a manuscript on natural analogues CO_2 leakage from subsurface reservoirs. The remaining section on the chemistry of the fluids is in progress.
- Improvements to CHEMTOUGH code to incorporate kinetic effects on reaction progress.
- Submission of two abstracts (based on the above work) to the topical session at the upcoming GSA meeting in Denver titled “ Experimental, Field, and Modeling Studies of Geological Carbon Sequestration”.
- Submission of paper to upcoming GGHT-6 conference in Kyoto. Co-PI S. White will attend this conference, and will also be involved in three other papers.

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Fig. 4. West of this area (lower Little Colorado River), the pressure intercept is close to 5000 ft asl. There is likely to be a transition zone between the two areas.

Figure 6.
Cross-section from the Little Colorado River travertine area and Springerville-St Johns CO_2 field (in structural high left of Salado Springs) to the lower Little Colorado River where ~~is~~ it passes Holbrook. Line of cross-section (A-B) is marked on Fig. 4.

EXECUTIVE SUMMARY

The priorities for the last quarter have been the study of two areas of natural leakage of CO2-rich fluids to the surface in central Utah and eastern Arizona, and improving the numerical code that simulates rock-fluid interactions so that it adequately handles kinetic reactions.

There are two areas of the Colorado Plateau where large volumes of carbon dioxide-rich fluids have leaked to the surface in recent geologic time and left characteristic signatures. These areas are in central Utah and in east-central Arizona. Both areas are being studied in this project because of their value as analogues of leaky CO_2 reservoirs that may be used for sequestering power plant CO_2. Extensive areas of travertine have been deposited over an area of up to 100 square miles, and the presence of several active bicarbonate-rich springs or geysers in both areas, in addition to proven CO_2 occurrences at depth show that the leakage is still occurring today. The two areas have not been noted for the presence of toxic effects of CO_2, prompting a preliminary observation that low levels of CO_2 leakage may have limited environmental impacts.

Fieldtrips to the central Utah and the eastern Arizona travertine areas took place during the last four months. Terraces of travertine up to 200 feet above the local drainages indicate that leakage of CO_2-rich fluids has been occurring for several hundred thousand years. Analysis of pressure trends in oil and gas exploration wells of the region show that the areas of travertine are draining deep basin waters that may be originating from over 100 miles away. The source of the CO_2 is less clear. A chemical study of the waters in both areas is in progress. This reports presents a draft paper describing the hydrogeology of the two areas, and an abstract on this work has also been submitted to the GSA meeting in Denver later this year.

Good progress has been on improving the reactive fluid transport code (chemTOUGH2) to include kinetic interactions between reservoir fluids and rocks. Initial attempts at this required very large amounts of computer time and it was not possible to continue the simulations long enough to get useful results. The method used to treat kinetic chemical reactions has been changed to allow several "chemical" timesteps to be taken for each flow calculation. This has overcome the problem and the final stage of the Farnham Dome calculations are underway and will be completed by the end of July. Phase II of the modeling will focus on large structures where lateral flow in near horizontal reservoir sequences is possible.

Papers on this work are being prepared for the GGHT-6 conference in Kyoto later this year, and an abstract has also been submitted to the GSA Denver meeting. The co-P.I. continues to participate in the intercomparison study between simulation codes coordinated by LBL.

EXPERIMENTAL

No experiments were carried out during the reporting period.

RESULTS AND DISCUSSION

Most work during this quarter has been involved with the study of natural areas of CO2 leakage on the Colorado Plateau, and with improving the numerical code so that the kinetic reactions could be calculated more rapidly. A draft manuscript has been prepared on the CO2 leakage areas has been prepared and is given below. It requires an additional section on the chemical characteristics of the fluids before being ready to submit to a scientific journal (not yet chosen). Additional work on the chemistry of the fluids in the analogue areas is in progress. Chemistry samples have been collected from eastern Arizona and are being analysed. Results will be reported in next quarter's report.

In addition, a Powerpoint presentation summarizing project progress up to June 2002 was prepared at the request of the DOE-NETL Project Manager (Perry Bergman) and submitted by email.

Two papers based on the above work have been submitted to the Denver GSA, October, 2002. Abstracts for these two papers are as follows:

CO_2 geysers, springs and massive travertine deposits in central Utah and eastern Arizona: examples of natural leakage of fluids saturated in CO_2.

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Abstract

Extensive travertine deposits occur over 50 - 100 square mile areas near the Green River in central Utah, and the Little Colorado River between Springerville and St. Johns in eastern Arizona. Both areas occur adjacent to fault zones with significant differential vertical displacement of Colorado Plateau strata. Analysis of drill stem pressure measurements from deep exploration wells, and potentiometric data from groundwater, springs and CO_2 geysers, suggests that these areas are outflow zones of deep basin fluids saturated in CO_2 originating from aquifers up to 1000 square miles in area. Older travertine caps terraces and forms domes that are up to 200 feet above the presently active seepage areas. Based on erosion rate estimates of less

than one foot per thousand years for the Colorado River system in Utah, the fluid outflow has been active for at least several hundred thousand years. These areas may be natural analogues for some of the potential effects of CO_2 leakage from subsurface reservoirs with imperfect seals.

Simulation of CO_2 injection near the Hunter power station, central Utah

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Abstract

Injection of CO_2 into deep saline aquifers is an attractive option for the long-term sequestration of the gas. The injection technology required is well proven in enhanced oil recovery by CO_2 injection projects. Modeling studies show that in some situations the gas is likely to be contained for very long periods of time and the existence of natural CO_2 reservoirs supports this conclusion.

Permanent sequestration of CO_2 can be achieved when the CO_2-rich brine reacts with reservoir rocks to form minerals. However there is evidence of leakage from the natural CO_2 reservoirs on the Colorado Plateau (Allis et al. 1991) and it is likely that artificial reservoirs created by sequestration projects may also leak through seal faults or by exceeding seal containment pressures. Mineral forming reactions are slow.

This paper investigates the injection of CO_2 into geological structures that are not dome shaped and thus do not provide the geology required for the development of an artificial CO_2 reservoir. Such structures may, however, provide very long flow paths between the injection point and the surface, allowing the permanent sequestration of the injected CO_2 as a mineral or dissolved in the groundwater. The geology beneath Hunter Power Plant, located in central Utah, is one example of such a structure. The sedimentary sequence contains potential reservoir and seal formations at over 1 km depth beneath the power plant, but the regional dip exposes some of these formations at the surface some 40 - 50 km away.

A two-dimensional numerical model of the groundwater in this area has been developed and used to investigate the long-term behavior of CO_2 injected beneath the power plant. The model represents the major physical and chemical processes induced by injection of CO_2 into the reservoirs including transport in the liquid and gas phases, the effect of dissolved CO_2 on brine density, and the reaction between the CO_2 plume and reservoir rocks.

We will discuss transit times to the surface for gas injected at different depths, the effectiveness of mineral and liquid phase sequestration, the effect of fault rupture creating high-permeability flow paths to surface, and the possibility of increased mineral deposition in such areas of focused flow providing a self sealing mechanism.

Analogues of CO_2 leakage – draft manuscript.

A full copy of the paper to be presented at the Annual GSA meeting in Denver, October, 2002, is included here. An additional section on the chemistry of the fluids is in progress and will be added to this paper before it is submitted to a scientific journal.

[Preliminary Draft (7/1/02)]

CO_2 geysers, springs and massive travertine deposits in central Utah and eastern Arizona: examples of natural leakage of fluids saturated in CO_2.

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Abstract

Extensive travertine deposits occur over 50 - 100 square mile areas near the Green River in central Utah, and the Little Colorado River between Springerville and St. Johns in eastern Arizona. Both areas occur adjacent to fault zones with significant differential vertical displacement of Colorado Plateau strata. Analysis of drill stem pressure measurements from deep exploration wells, and potentiometric data from groundwater, springs and CO_2 geysers, suggests that these areas are outflow zones of deep basin fluids saturated in CO_2 originating from aquifers up to 1000 square miles in area. Older travertine caps terraces and forms domes that are up to 200 feet above the presently active seepage areas. Based on erosion rate estimates of less than one foot per thousand years for the Colorado River system in Utah, the fluid outflow has been active for at least several hundred thousand years. These areas may be natural analogues for some of the potential effects of CO_2 leakage from subsurface reservoirs with imperfect seals.

Introduction

One of the most famous active travertine deposits occurs at Mammoth in northern Yellowstone National Park. Here, water that has infiltrated Paleozoic sediments beneath the Gallatin Mountains encounters high temperatures and CO_2 at depth, and after rising to the surface along adjacent caldera boundary faults, deposits spectacular travertine terraces upon loss of dissolved CO_2. In contrast to the Mammoth deposit, two areas of similarly extensive travertine deposits in central Utah and eastern Arizona have received scant attention, largely because of the paucity of spring activity and active travertine deposition. These two areas are the subject of this paper.

Increasing interest by the U.S. Department of Energy in geologic sequestration of CO_2, particularly if it becomes economic to separate CO_2 from the flue gases of fossil-fueled power plants, has raised questions about the long-term fate of injected CO_2. In our study, the natural CO_2 fields that occur around the Colorado Plateau and Southern Rocky Mountains region are used as analogues of geological sequestration of CO_2. One aspect of this research is the possible environmental effect if CO_2 leaks towards the surface. Most geothermal fields and active volcanoes are sites of CO_2 outflow as well as other gases such as H_2S or SO_2. However, most sites for future geologic sequestration of CO_2 are likely to be in a sedimentary environment rather than a volcanic environment, where low permeability sediments ideally provide a seal to the injected CO_2. Therefore, sedimentary areas where CO_2 has been, or is, leaking to the surface are of particular interest.

In this paper we discuss preliminary findings about the hydrology of two large travertine areas in central Utah and eastern Arizona. Both the Green River area (central Utah) and the Little Colorado River area (eastern Arizona) are underlain by typical Mesozoic and Paleozoic sediments of the Colorado Plateau. In the Little Colorado River area, Tertiary sediments and Quaternary basalts are also present (Sirrine, 1951; Crumpler et al., 1994). The map in Figure 1 shows their general locations, as well as the locations of other proven CO_2 fields around the Colorado Plateau and Southern Rocky Mountain region. Both areas have been targets of oil and gas exploration. At Green River, three CO_2 geysers are in fact abandoned exploration wells. The Little Colorado River travertine area is adjacent to, and partially overlies, a proven CO_2 field that Ridgeway Arizona Oil Corporation is presently developing. Much of the data for this paper has been taken from oil exploration industry files (e.g. PI /Dwights information base), and this has been supplemented by data contributed by Ridgeway and Tucson Electric Power (TEP), which operates a coal-fired power plant on the CO_2 field.

Green River Travertine Area

Although there are isolated occurrences of travertine and tufa adjacent to the Green River between its junction with the San Rafael River in the south and Little Grand Wash Fault in the north (12 miles), most travertine occurs immediately adjacent to the Little Grand Wash fault and the Ten Mile Graben (Baer and Rigby, 1978; Doelling, 1994; Fig. 2). These two fault zones cut north-dipping, weakly anticlinal structures. In both cases the displacement on the faults in the vicinity of the main travertine areas is 600 – 700 feet. Actively flowing features and older travertine are present in both areas. All active features have static water levels of between 4000 and 4100 feet above sea level (ft asl). The maximum temperature for the surface waters is less than 10 °C above ambient. Crystal Geyser is the most well known feature on the Little Grand Wash fault. The geyser erupts from an abandoned standpipe, and is precipitating yellow-brown carbonate in the form of miniature terraces, typical of rapidly overflowing spring waters saturated in bicarbonate. Eruptions are intermittent (4 – 24 hours interval), and typically last for 5 – 15 minutes with the maximum column height up to 90 feet. Between 1968 and 1973, the eruption volume was 0.1 acre-feet (120 m^3 Baer and Rigby, 1978). Travertine precipitated from the geyser activity overlies older aragonite mounds, and this area is surrounded by travertine and tufa terraces at several higher elevations. The most extensive travertine terraces are at the highest elevation, which are up to 200 feet above the present river level. The age of the oldest terraces is estimated to be at least 200,000 years, based on erosion rates of less than 0.8 feet/thousand years (Doelling, 1994).

Discontinuous travertine and tufa extend along the northeast side of Ten Mile Graben for a distance of about 2 miles. It occurs at five different elevations, and in places drapes over faults. The textures on the draped travertine suggest it formed as overflowing water cascaded down from a more elevated discharge feature, very similar to a larger scale bank of draped travertine seen in the Little Colorado River area (discussed below). Active features at Ten Mile Graben include the relatively unimpressive Ten Mile Geyser and a pool located on a travertine mound 80 x 140 feet in diameter and 2.5 feet above the surrounding ground surface. This pool overflowed at about 2 l/min (0.5 gal/min) and had several gas discharge points in the early 1990s. It has subsequently been excavated, and now has no overflow, although gas continues to bubble at one end of the pool. Erosion adjacent to some of the travertine terraces has exposed conduits in the underlying Jurassic sediment, where the normally red sandstone has been extensively bleached by the ascending fluids.

Hydrology of Green River Travertine Area

When data from oil and gas exploration wells in the general region of the Green River travertine area is compiled, some insight to the origin of the waters is gained. Firstly the major element chemistry of Crystal Geyser shows some similarities to the Permian White Rim sandstone feedzone water in the Mountain Fuel well 5 miles to the southeast (Table 1). Deeper water samples from the Mountain Fuel well show progressively more mineralized water, with sodium chloride becoming more dominant with depth. This reflects the presence of Paradox salt deeper in the Paleozoic section beneath the region. The Crystal Geyser water is therefore unlikely to have risen vertically from within the Paradox Basin. Mayo et al., (1991) suggest that the Crystal Geyser water has picked up excess CO_2 from an external source (i.e. not local carbonate dissolution), and the high sulphate concentration is consistent with gypsum dissolution. Although the water has a relatively high sodium chloride concentration, it has not flowed through bedded halite.

Baer and Rigby (1978), and Mayo et al., (1991) suggest that the water is meteoric and that it may have infiltrated outcropping Mesozoic sandstones along the eastern flank of the San Rafael Swell. While not conclusive, a compilation of shut-in pressures from drill stem tests in exploration wells suggests that the water could have originated from farther to the northwest, perhaps from beneath the Wasatch Plateau or northern Book Cliffs (Fig. 2). Pressures have been plotted at the mid point elevation of the open zone during the test (Fig. 3). Two dominant pressure trends exist over an area of at least 100 by 100 miles. Given the uncertainties inherent in drill stem pressure measurements, the two trends are each approximately on a hydrostatic gradient, suggesting control by two (or more) laterally extensive aquifers. There are likely to be more subtle lateral pressure gradients with these aquifers, but because of the scatter in the data, they are not obvious. The lower elevation trend extends to at least the eastern margin of the Wasatch Plateau, and it has a zero-pressure intercept of close to 4000 ft asl. This is the same elevation as the static head of the flowing features in the Green River travertine area.

The aquifer trend at higher elevation has a zero pressure intercept of close to 6000 ft asl. The trend is restricted to beneath the Wasatch Plateau and it extends eastwards into the Ferron coal measures trend (roughly delineated by squares, Fig. 2). In two wells in the Ferron area, shallow pressures fall on the upper trend, and deep pressures fall on the lower trend. The transition between the two trends occurs at about sea level. Inspection of the sedimentary sequence suggests that the fine-grained sediments of the lower Mesozoic Moenkopi-Chinle Formations are acting as a regional aquiclude. The laterally extensive aquifer units may be the Permian White-Rim sandstone beneath this aquiclude, and the Jurassic Entrada-Navajo-Wingate sandstones above the aquiclude. We suspect that the source of the high bicarbonate waters in the Green River travertine area could be to the northwest, possibly from as far away as the Wasatch Plateau. This would allow for a more potent recharge source (about 30 inches of precipitation per year) than would be the case from recharge on the San Rafael Swell (< 10 inches per year with theoretical evapotranspiration five times precipitation; Division of Water Rights, 2000).

Location	Green River UT	Green River UT	Green River. UT	Little Col. R. AZ	Little Col. R. AZ	Little Col. R. AZ
Sample type	Downhole sample	Drill stem test	Drill stem test	Surface discharge	Production sample	Production sample
Site name	Crystal Geyser	Mountain Fuel 1-25	Mountain Fuel 1-25	Salado Springs	TEP P-7	Ridgeway 11-21
Date	1992	3/21/1973	3/21/1973	10/18/2000	7/12/2000	5/18/1999
Elevation (ft asl)	4,060	4,132	4,132	5,840	6,560	6,932
Depth (ft)	?	2,595	9,250	0	800	2,000
Formation	?	White Rim sst	Leadville lst	?	Kaibab lst - Glorieta sst	Supai Fm. Amos Wash
pH	6.4			7.1	6.7	7.1
TDS	16,400	16,966	200,249	2,150	1,200	4,210
Sodium	2,251	5,704	64,376	340	180	804
Calcium	2,144	515	9,555	330	170	110
Potassium	154	170	2,700	26	20	174
Magnesium	400	120	1,196	63	42	232
Chloride	3,236	8,000	10,000	660	230	483
Sulfate	2,080	1,550	1,200	610	330	1,540
Bicarbonate	6,162	1,842	451	560	360	1,190

Table 1. Comparison of water sample chemistries from a near-surface feature and two nearby wells for each of the travertine areas. The Crystal Geyser analysis is from Mayo et al., (1991), and an attempt was made to sample the discharge below the gas exsolution zone in the upper part of the well; the Mountain Fuel analyses are from UGS files, and are assumed to have been collected at the wellhead, possibly after gas separation. TEP provided the Salado Springs and P-7 analyses and Ridgeway Arizona Oil Corporation provided the 11-21 analysis. Both the P-7 and the 11-21 samples are at the wellhead, after any gas separation.

Little Colorado River Travertine Area

The Little Colorado River travertine area is situated between Springerville and St Johns (Fig. 4), and it is also the location of several seepage areas including some cool springs and pools adjacent to the river. The greatest concentration of travertine occurs adjacent to a 6-mile length of the river between Lyman Lake and Salado Springs. Descriptions of the travertine have been published by Sirrine (1951) and Crumpler et al. (1994), and are summarized here. Large travertine sheets, the largest being 4 by 2 miles in extent, occur adjacent to seepage areas as well as on terraces several hundred feet above the valley floor. Many circular domes occur, ranging up to 2000 feet in diameter, and often with central craters marking the original overflow location. The height of the cones is often difficult to determine because the travertine frequently caps raised terraces of sediment (typically red Moenkopi Formation), and travertine often drapes over terrace margins making the depth to sediment beneath the crater uncertain. Based on assumptions about the elevation of the underlying sediment platform, most of the domes have travertine thicknesses ranging in height from less than 10 up to about 200 feet. All pools and springs appear to be no more than 10 °C above ambient.

We agree with the observation by Crumpler et al. (1994) that these very large symmetrical travertine domes are unusual and are largely unstudied (e.g. not described by Chafetz and Folk, 1984). Presumably they point to a long history (perhaps as great as 10^4 - 10^5 years assuming similar erosion rates to those in central Utah) of continued outflow with a nearly constant head from the same vent positions. A lateral flow towards the vent, rather than a near-vertical upflow path from depth, also seems to be necessary to minimize clogging of the vent over time due to CO_2 exsolution and carbonate precipitation. No active gas emissions were noted in our recent field visit, nor have any been reported in the literature. Perhaps the CO_2 is separating from the water within the structural high to the east of the springs and travertine deposits, and may be leaking diffusely into the overlying, thick vadose zone in that area (assuming steady state outflow conditions).

Hydrology of the Little Colorado River Travertine Area

All flowing features in the travertine area appear to be less than 10 feet above the elevation of the Little Colorado River, suggesting that the river is the primary control on the outflows. Some of the pools had no obvious overflow, and presumably were leaking below the ground surface. The greatest outflows appeared to be in a swampy area immediately below the Lyman dam (estimated to be about 10 l/s [150 gal/min]), and in the swampy area of Salado Springs (about 15 l/s [225 gal/min]).

The chemistry of the Salado Spring waters is shown in Table 1. The water has a mixed ion composition with a total dissolved solids (TDS) concentration of close to 2000 mg/kg. This is significantly more dilute than the water compositions from the Green River travertine area. The Salado Springs water is similar to an analysis from groundwater wells in the TEP Springerville Generating Station's well field 10 - 16 miles to the southeast. These wells tap an aquifer in the Kaibab limestone-Glorieta (Coconino-White Rim equivalent) sandstone (stratigraphically immediately beneath the Moenkopi Formation that crops out at Salado). This fractured and cavernous aquifer (Rauzi, 1999) has a head 100 to 200 feet higher than the elevation of Salado Springs. The TEP groundwater is not quite as concentrated as the Salado Spring water, and it has a lower pH.

The production water from about 1000 feet deeper in Ridgeway's CO_2 reservoir has twice the TDS of Salado Spring water, with the main differences being a greater sulfate concentration. This is attributed to the presence of anhydrite in the reservoir (Supai Formation), which often forms a seal that traps the CO_2 gas (Rauzi, 1999).

Fig. 5 shows the pressure-elevation trends for the Little Colorado River area being considered here. Two trends are apparent, with pressures coded by location on Figs. 4 and 5. The travertine – CO_2 field forms one obvious hydrological unit (aquifer) with a pressure intercept of close to 6000 feet asl. The TEP groundwater wells have been plotted collectively by showing an average head (zero pressure) at 6000 feet asl. Actual water levels rise to over 6200 feet asl on the east side of the Salado Springs fault zone (TEP data). The scatter in pressure from the Ridgeway wells could be consistent with localized zones of CO_2 causing slightly high pressures at the top of the gas zones, but the overall near-hydrostatic trend shows the system is water-dominated. This pressure trend explains how the springs and pools adjacent to the Little Colorado River travertine area could be fed by a lateral outflow of water from the region of the CO_2 field.

Within about 5 – 10 miles west of Salado Springs, the pressure trend is significantly different, and indicates a laterally extensive aquifer system that has a pressure intercept at about 5000 feet above sea level. This elevation is similar to that of the Little Colorado River about 10 miles west of Holbrook. It is possible that the Kaibab-Glorieta aquifer is in pressure equilibrium with surface water in that location. The cross-section in Fig. 6 illustrates this lateral change in potentiometric head and compares it to the gross structural changes in some of the main sedimentary units. The transition between the two pressure trends is poorly controlled. Perched groundwater aquifers may overly the deep pressure trends identified here.

Conclusions

In both central Utah and eastern Arizona, unusually extensive sheets of travertine crop out over areas of 50 – 100 square miles. Active, bicarbonate-rich geysers, springs and pools exist within travertine deposits on the valley floors, but large terraces of travertine are also perched up to 200 feet above the valley floor. The deposits indicate a sustained period of outflow of fluid saturated in bicarbonate for at least 200,000 years, based on accepted erosion rates. However, the amount of active carbonate precipitation today seems to be rather small and relatively insignificant compared to the amount of past deposition. We speculate that either the climate is drier and the amount of water outflow is significantly diminished at the moment, or that the CO_2 flux at depth has diminished, and the dissolved CO_2 content in the outflowing water is lower. Given that both areas show the same pattern of apparently diminished precipitation rates, we favor the drier climate explanation.

In both areas, significant lateral flow of the water has occurred, and we suspect that CO_2 may have become separated from the water along the outflow path. In eastern Utah, the travertine area may be the main outflow for the Permian (White Rim sandstone) and possibly deeper aquifers which cover about 100 miles by 100 miles. The recharge zone for this aquifer appears to be the Wasatch Plateau to the northwest of the travertine area. Two CO_2 fields, Gordon creek and Farnham Dome (Fig. 1), exist in this area. In eastern Arizona, Permian Kaibab-Glorieta sandstone units and the underlying Supai Formation act as one aquifer that extends at depth at least 20 miles to the east and south of the travertine area.

Although travertine deposits are commonly associated with geothermal springs (e.g. Mammoth area of Yellowstone National Park), there are no obvious geothermal indicators associated with the two travertine areas discussed here. The Green River travertine area lies centrally within the Colorado Plateau where the heat flow is low and known to be about 50 mW/m^2 (Hendrikson, 2000). No new information from the oil industry well data analysed for pressure trends in this work suggests that a high temperature resource is present in this area. Stone (1980) reviewed the geothermal information known about the Springerville-St Johns area and concluded, based on elevated silica concentrations in groundwater and one poorly constrained heat flow measurement, that the evidence "supports the probability of a geothermal resource in this area." The temperature of the pools and springs in the region do not exceed 10°C above ambient. The Ridgeway CO_2 wells drilled since Stone's report provide more information, because the well logs record bottom hole temperature measurements. The data is very scattered, but bottom hole temperatures soon after drilling ceased were 33 – 47 °C at depths of 1800 – 3200 feet. These measurements were typically made between 2 – 5 hours after circulation of drilling fluids ceased.

Allowing for uncertainties in the extent of thermal recovery, and uncertainties in the appropriate annual average surface temperature as well as possible effects of an extensive vadose zone, the vertical temperature gradient is unlikely to exceed 25 - 30°C/km. The heat flow is likely to be in the range 50 – 90 mW/m^2, so the new information suggests that this area is unlikely to contain a significant geothermal resource at reasonable depths.

Acknowledgements

We thank Tom White at Ridgeway Arizona Oil Corporation for discussions about the CO_2 system near Springerville, and help in obtaining chemical analyses of the ground waters. Jeff Hammond at TEP was also very helpful in sharing information about the groundwater characteristics of the area. This project is being supported by a grant from the Department of Energy (# DE-FC26-00NT4096, Program Manager Perry Bergman), the Utah Department of Economic and Community Development, and by the Utah Geological Survey.

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Fig. 1. Location of the two travertine areas adjacent to the Green River, Utah, and the Little Colorado River, Arizona. Natural CO_2 reservoirs are also highlighted (after Allis et al., 2001).

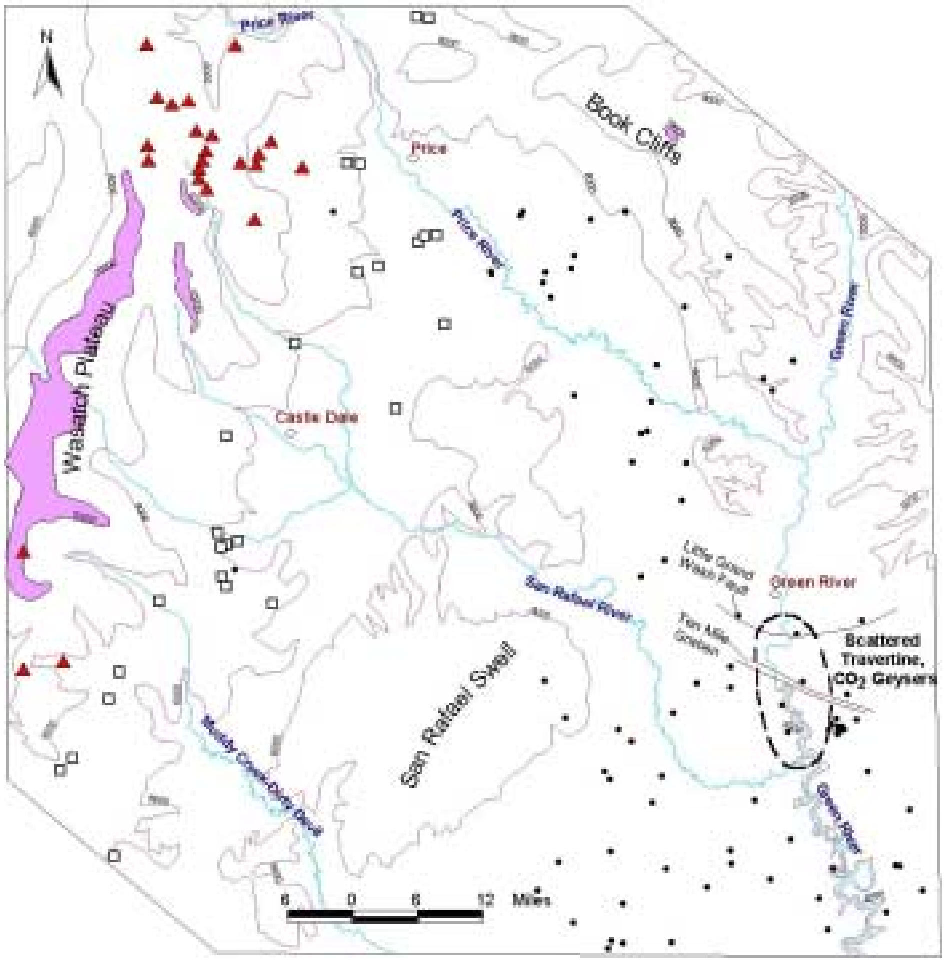

Fig. 2. Green River travertine area (dashed outline) with locations of exploration wells where shut-in drill stem tests show control by an aquifer with a head of about 4000 ft asl (dots), and with a head at about 6000 ft asl (triangles). Squares are wells in a transition zone that typically follows the upper head trend above sea level, and lower head trend below this elevation. Topographic contours every 2000 feet; topography above 10,000 ft asl shaded.

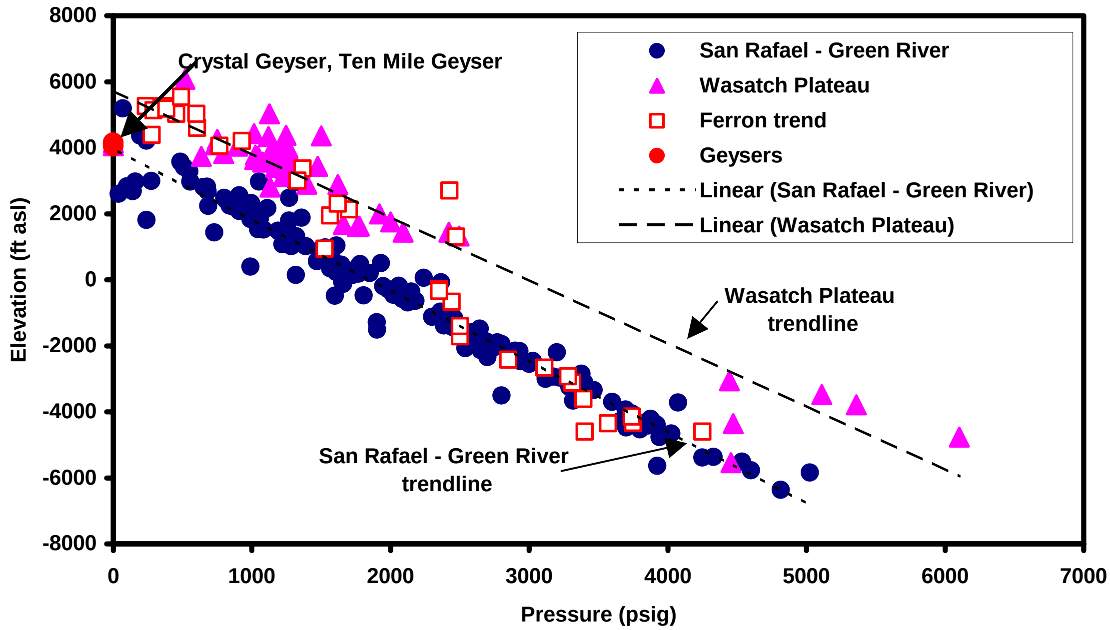

Fig. 3: Pressure versus elevation showing much of the Green River-San Rafael area has pressure intercept at 4000 ft asl, consistent with discharge in travertine area. Symbols refer to Fig. 2.

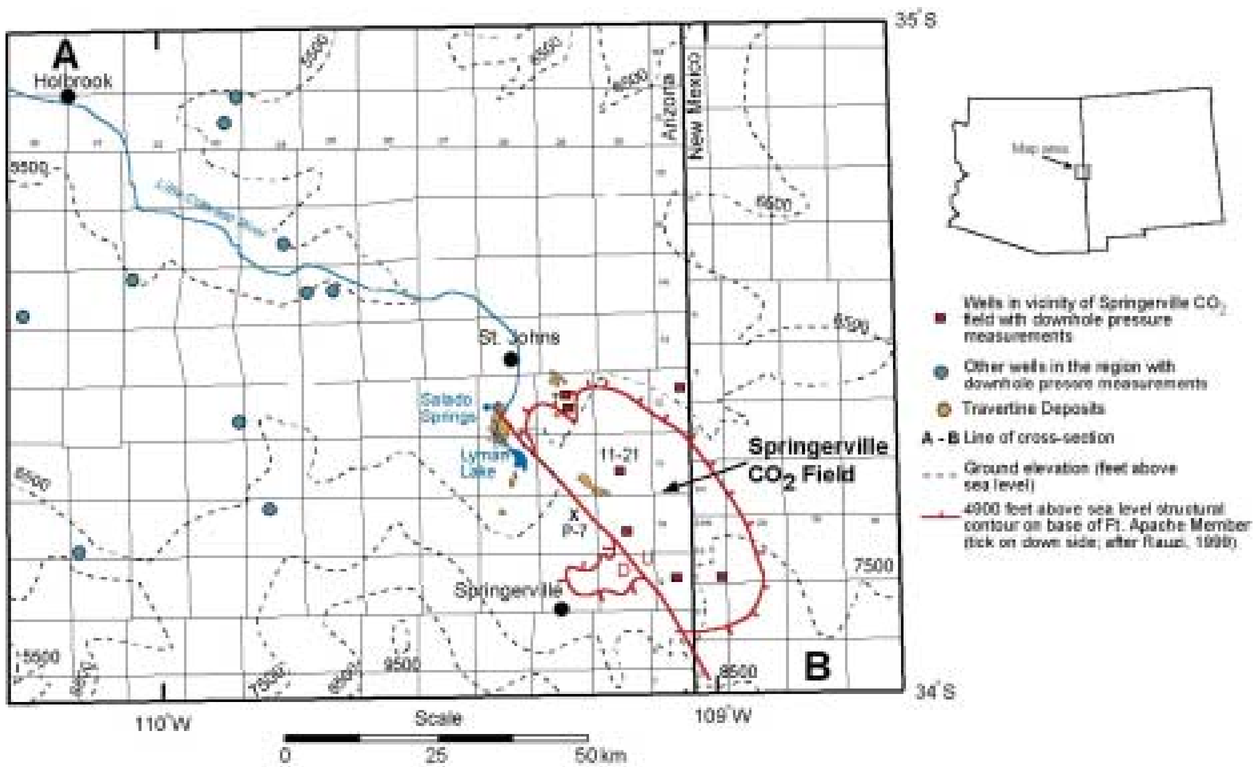

Fig. 4. Location of the Little Colorado River travertine area and the adjacent CO_2 field. Squares and dots are wells with shut-in pressure measurements (see Fig. 5). Topographic contours every 1000 feet.

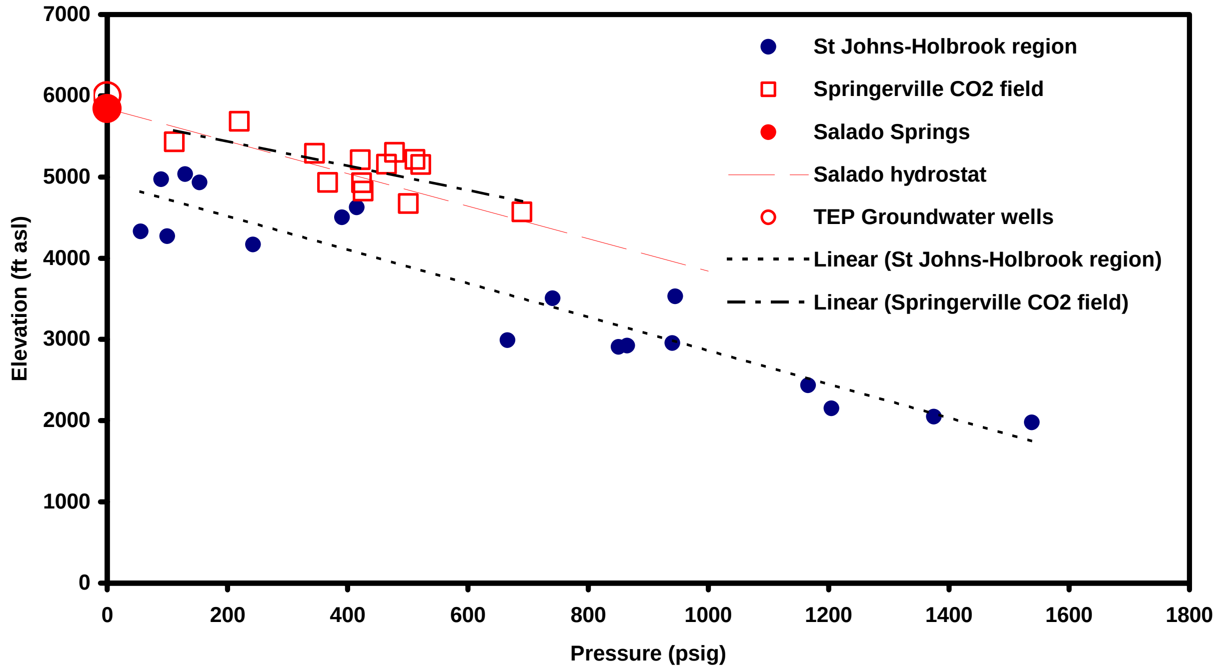

Fig. 5: Pressure versus elevation showing much of the Little Colorado River travertine area and the CO_2 has pressure intercept at 6000 ft asl, consistent with discharge in travertine area. Symbols refer to Fig. 4. West of this area (lower Little Colorado River), the pressure intercept is close to 5000 ft asl. There is likely to be a transition zone between the two areas.

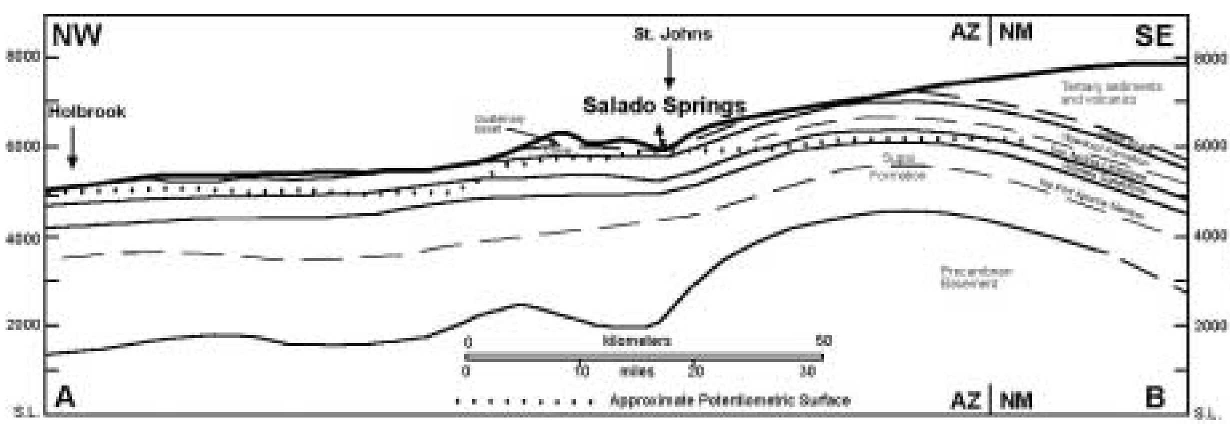

Fig. 6. Cross-section from the Little Colorado River travertine area and Springerville-St Johns CO_2 field (in structural high left of Salado Springs) to the lower Little Colorado River where ~~is~~ it passes Holbrook. Line of cross-section (A-B) is marked on Fig. 4.

2. Progress in numerical modeling of fluid-rock interactions

Farnham Dome

Laboratory experiments suggest that at low temperatures interactions between CO_2 rich fluids and reservoir rocks typical of those found in the natural CO2 reservoirs of the Colorado Plateau are very slow. Equilibrium is likely to be reached only in many hundreds of years. The observed mineralogy in many of the units at Farnham Dome supports this conclusion with the observed mineralogy violating the Gibbs Phase law. This implies the reservoir fluids are not in equilibrium with the reservoir minerals although simplifying the mineral assemblage and assuming equilibrium with reservoir fluids did give a reasonable match to the generally chemical trends.

To model the chemistry of system the interaction between reservoir fluids and rocks must be treated kinetically. Initial attempts at this required very large amounts of computer time and it was not possible to continue the simulations long enough to get useful results. The lengthy computational time is the result of technique originally used by ChemTOUGH2 to couple chemistry with fluid flow. The time step used for flow calculations and kinetic chemistry calculations are the same and this forced more expensive flow calculations to be done than were required for numerical stability or accuracy.

The method used to treat kinetic chemical reactions has been changed to allow several "chemical" timesteps to be taken for each flow calculation. This has overcome the problem and the final stage of the Farnham dome calculations are underway and will be completed by the end of July.

Intercomparison study between simulation codes

An intercomparison study between simulation codes for terrestrial sequestration of CO_2 has been run by LBNL and contributions were made to several of the problems. The objectives of the study were

- to determine and evaluate key processes through numerical simulation
- to explore the strengths of different codes
- and to achieve acceptance of such codes for use in the development of geologic systems for CO_2 disposal.

Contributions were made to problems on

- Mixing of Stably Stratified Gases
- Advective-Diffusive Mixing Due to Lateral Density Gradient
- Radial Flow from a CO_2 Injection Well
- CO_2 Discharge Along a Fault Zone
- Mineral Trapping in a Glauconitic Sandstone Aquifer
- CO_2 Injection into a 2-D Layered Brine Formation

GGHT-6 Conference

Several papers are to be presented at the GGHT-6 conference being held in Kyoto in October. The first of these is co-authored by this project team while the others have been contributed to by a number of institutions, co-PI S. White as a co-author of each abstract. S. White will be attending this conference on behalf of the team.

Natural CO_2 Reservoirs of Colorado Plateau and Southern Rocky Mountains. (Accepted for oral presentation)

Code Intercomparison Builds Confidence in Numerical Models for Geologic Disposal of CO_2. (Accepted for oral presentation)

Mixing of CO_2 and CH_4 in gas reservoirs: Code Comparison Studies. (Poster)

Mineral Trapping in a Glauconite Sandstone Aquifer. (Poster)

CONCLUSIONS

The main achievements during this quarter have been:

- Field trips to the central Utah and eastern Arizona travertine areas to collect data and water samples to support study of surface fluid leakage in these two areas
- Partial completion of a manuscript on natural analogues CO_2 leakage from subsurface reservoirs. The remaining section on the chemistry of the fluids is in progress.
- Improvements to CHEMTOUGH code to incorporate kinetic effects on reaction progress.
- Submission of two abstracts (based on the above work) to the topical session at the upcoming GSA meeting in Denver titled " Experimental, Field, and Modeling Studies of Geological Carbon Sequestration".
- Submission of paper to upcoming GGHT-6 conference in Kyoto. Co-PI S. White will attend this conference, and will also be involved in three other papers.